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SUPERSONIC LAMINAR FLOW CONTROL RESEARCH

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Technical Objectives

The objective of the research is to understand supersonic laminar flow stability, transition and active control. Some prediction techniques will be developed or modified to analyze laminar flow stability. The effects of supersonic laminar flow with distributed heating and cooling on active control will be studied. The primary tasks of the research applying to the NASA/Ames POC and LFSWT's nozzle design with laminar flow control are as follows:

1. Predictions of supersonic laminar boundary layer stability and transition,

2. Effects of wall heating and cooling for supersonic laminar flow control, and

3. Performance evaluation of POC and LFSWT nozzles design with wall heating and cooling effects applying at different locations and various length.

Accomplishment of the First Year (Refs. 1 & 2)

A. Prediction of Supersonic Laminar Boundary Layer and Stability

Two Computational Fluid Dynamics (CFD) codes which are used to conduct this study have been checked out successfully in the first half year. The first one is a boundary layer code developed by Harris at NASA (Ref. 3). This program solves the laminar, transitional, or turbulent compressible boundary layer equations for two dimensional or axisymmetric flows. The output of this code is used as inputs for the second CFD code developed by a NASA's contractor Malik (Ref. 4). This second program utilizes the compressible linear stability theory to predict the stability characteristics and the transition location of the boundary layer.

B. Temperature effects on the Stability Analysis of the Laminar Boundary Layer of a Flat Plate

The temperature effects on the stability of the laminar boundary layer was analyzed for a flat plate at M = 1.6. The wall heating was applied to the leading edge ten percent of the flat plate and the rest of the plate was remained at the adiabatic wall temperature. Three cases of heating temperatures are input into the boundary layer codes ranging from 602°R, 702°R to 902°R with the adiabatic wall temperature case (502°R). They all increase the stability of the boundary layer with the results of N factor getting smaller as the heating temperature increases. Details are reported in the Semi-Annual Report #1 (Ref. 1) as well as Lafrance's thesis (Ref. 5). These findings are consistent with theoretical results obtained for the subsonic flow in Ref 6.

C. Results of the POC nozzle with Local Strip Heating

Since the local strip heating can enhance the stability on the flat plate (i.e., without pressure gradient), it is reasonably expected to apply the idea to the nozzle (i.e., with pressure gradient along the wall) in order to enhance the stability of the wall boundary layer.

One typical case is given here to illustrate the feasibility of search of the optimal locations and increment of temperature from wall heating. Local heating and cooling strips are applied at $2.86 \le X \le 3.73$ downstream of the nozzle entrance as station X=0 at 600°R and 400°R, respectively. The total length of the NASA PoC nozzle and test section from the nozzle entrance to the test-section exit is 9.23 units. Both results obtained from the curvature criteria and N-factor theory have presented the consistent conclusion, i.e., the heating strip stabilizes the boundary layer. Details of these results and other cases are given in Section 2.3 and 3.3 of Meredith's master thesis (Ref. 7).

Status of Progress

A. Prediction for Laminar Flow Supersonic Wind Tunnel (LFSWT)

This Laminar Flow Tunnel is 5.505 ft long including the nozzle and the test section. The throat of the nozzle is located at 0.557 ft downstream the nozzle inlet plane. Five locations of heating and cooling strip have been investigated. Three locations upstream of the instability on-set point are investigated the effectiveness of the heating and cooling on the boundary layer stability. Two locations downstream of the instability on-set point were applied to heating and cooling strips.

The effect of removing heat energy to enhance the boundary layer stability should be properly located either using heating or cooling strips. The location of the strip is critical to the distance from the on-set point of boundary layer instability. In order to enhance the stability, in general, the heating strip should be applied upstream of the instability on-set point and the cooling strip

downstream of the on-set point.

Furthermore, it is interested to apply two strips on the wall: one heating strip upstream of the instability on-set point and the other cooling strip downstream of the stability on-set point. Based on the above discussion, it is expected that the two strips arrangement will enhance stability and reduce N-factor greatly. All results are given in the paper (Ref. 8) as shown in Appendix I.

B. Discussion of Results

The current findings indicate that the stability is enhanced as the heating is applied at the upstream of the boundary layer instability initiated point. On the other hand, the cooling at the downstream of the instability on-set point also increases the stability of the boundary layer and it is even more effective than those of upstream heating.

These may be rationalized as follows. The heating energy flowing downstream creates a positive temperature gradient in the vicinity of the wall ahead of the instability occurring location. This produces a cooling effects in the region near upstream and downstream the instability location and therefore enhances the boundary layer stability. The stability is reduced as the cooling is utilized at the same location, since it produces heating effects at the instability point. The equivalent effects can be obtained by cooling the wall downstream the instability on-set point. These results have been shown the same effects as the previous studies except that the present mechanism of cooling or heating is localized and limited in certain upstream region of the wall, e.g., the leading edge (10%) of the flat plate or a region downstream of the nozzle throat. The latest theoretical study by Masad & Nayfeh (Ref. 6) has provided similar results of heating effects which are limited to the subsonic flat plate case only. The experimental evidence obtained by Demetriades (Ref. 9) recently has also indicated a similar trend by heating the throat region's wall to enhance the stability or delay the transition in the boundary layer of a supersonic nozzle. The application of strip heating and/or cooling to the quiet-tunnel's wall for the boundary layer control seems feasible, especially since the heating and/or cooling regions are within a limited range of segments.

C. Publications

Two publications were written and published in the open literature. The results of the first year study are summarized in a journal paper entitled "**Wall Temperature Effects on the Stability of Laminar boundary Layer**" (Ref. 10) to be published in the ***AIAA Journal of Aircraft*** (enclosed in Appendix II).

A conference paper was presented in the 26th AIAA Fluid dynamics Conference, June 19-22, 1995 in San Diego. The paper is entitled " **Laminar Flow Control with Wall Temperature distribution for Quiet Supersonic wind Tunnels,** " AIAA 95-2296, June 1995 (Ref. 8) (enclosed in Appendix I).

Future Plan

- Calculate temperature effects on the Laminar Flow Supersonic Wind Tunnel (LFSWT) nozzle to apply distributed temperature profiles rather than constant temperature strips. The distributed temperature profiles are simulated to the actual experimental implementation.

- Select heating and cooling distributions to obtain the optimal configurations to calculate and enhance the laminar boundary layer stability.

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8. Lo, C. F., Lafrance, R., Meredith, W. S., Wiberg, C. G. and King, L. S. "Laminar Flow Control with Wall Temperature Distribution for Quiet Supersonic Wind Tunnels," AIAA 95-2296, June 1995.

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AIAA 95-2296
Laminar Flow Control with Wall Temperature Distribution for Quiet Supersonic Wind Tunnels

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Laminar Flow Control with Wall Temperature Distribution for Quiet Supersonic Wind Tunnels

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Abstract

The stability of laminar boundary layer control has been studied by the use of regionally distributed heating/cooling strips on laminar flow supersonic wind tunnel walls. The present results show that judicious placement of distributed wall temperature by heating/cooling strips can enhance laminar boundary layer stability. Methods used to depict the stability state are a stability modifier criterion based on curvature of the boundary layer velocity profile and a spatial linear stability code to compute N factors for Tollmien-Schlichting waves. The effects of a heating strip located upstream of the instability on-set point and a cooling strip downstream of the instability on-set point can enhance the stability state of the laminar boundary layer of supersonic tunnels with the M = 1.6 nozzle. The downstream cooling strip more effectively increases the stability than the upstream heating strip.

Nomenclature

h	= nozzle throat height
L	= distance from nozzle entrance
N	= N-factor in e^N for Tollmien-Schlichting Wave
M	= free-stream Mach Number
u	= boundary layer velocity in the x-direction
u"	= second velocity derivative in x-direction
p	= pressure
x,y	= coordinates in streamwise and normal directions
T_{aw}	= adiabatic wall temperature, in °R
T_w	= wall temperature, in °R
μ_w	= viscosity coefficient

Introduction

A unique, low-disturbance supersonic wind tunnel is being developed at NASA-Ames to advance supersonic laminar flow studies at cruise Mach numbers for the High Speed Civil Transport. The distinctive aerodynamic features of this new quiet tunnel will be a low-disturbance settling camber, laminar boundary layers on the nozzle walls, and steady supersonic diffuser flow.

A 1/8th-scale pilot version of the Laminar Flow Supersonic Wind Tunnel (LFSWT), called Proof-of-Concept (PoC) supersonic wind tunnel, was constructed and tested successfully without boundary layer control[1]. It is anticipated that design requirements of the nozzle for the full-scale LFSWT at the high pressure flow condition will include active control to the boundary layer on the nozzle wall or test section wall to maintain a laminar boundary layer. In other words, the active control of supersonic transition on the nozzle wall and/or test section wall is necessary to preserve the laminar boundary layer. Because of the novel drive system, there is no easy way to implement a suction-type boundary layer device such as the one in the Supersonic Low-Disturbance Pilot Tunnel[2] at NASA-Langley. The alternative is to use heating or cooling distributed along the nozzle wall and test section wall before the instability of the boundary layer is initiated.

Therefore, the effects of distributed wall surface temperature by heating and cooling for active control on supersonic laminar flow will be studied in the present paper. The primary task of the research applies the boundary layer control technology to the NASA/Ames PoC and LFSWT's nozzle design and test section. Analysis and prediction were performed on the PoC and LFSWT tunnels. The optimal temperature distribution is sought for as the guideline for the experiments.

Methods of Approach

The methods used to characterize the state of the stability are 1) Stability Modifier criterion[3] based on the curvature

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of the boundary layer velocity and 2) a spatial linear stability method to compute N-factors for Tollmien-Schlichting waves[4]. The latter method may be used to predict the transition on-set location empirically as N-factor = 9 to 11. The calculation is carried out by two basic CFD codes: a compressible boundary layer code by Harris[5] and a linear stability code by Malik[6]. The detailed boundary layer velocity profiles calculated by the boundary layer code are utilized to qualitatively analyze the state of boundary layer stability based on the Stability Modifier criterion[3]. The outputs of the boundary layer code also provide the inputs into the Malik's Stability code to determine the value of the N-factor. The results of these two criteria have indicated the consistent prediction for the state of the boundary layer stability.

The present approach is to study a flat plate case which is given in detail in the Appendix to illustrate the procedure[7]. Since the application of the method is successfully applied to the flat plate, the same method is used to investigate the laminar boundary layer control for quiet supersonic wind tunnels in the following section.

Results

The wall temperature effects on the stability of the laminar boundary layer are investigated on two supersonic wind tunnels, whose total freestream pressure, temperature and density are 10.0 psia, 530°R and 0.001583 $lb_f\text{-}s^2/ft^4$, respectively. With specific temperature distribution by heating or cooling on the nozzle and test section wall, the stability of the laminar boundary layers is examined to determine the effects on the boundary layer stability characteristics, either enhancing or destabilizing. Subsequently, the supersonic laminar flow can be controlled by temperature distribution along the wall at specific locations on the two quiet supersonic wind tunnels.

Stability on two Supersonic Wind Tunnels

(1) Proof of Concept (PoC) Quiet Supersonic Wind Tunnel with Mach Number 1.6 Nozzle

The total length of the NASA PoC nozzle and test section from the nozzle entrance to the test-section exit is 9.24 inches (was extended one inch in the length of the test section during the calculation, otherwise, this is 1/8 scale of the LFSWT in the next section) as shown in Fig. 1 with heating and cooling strips marked. The throat of the nozzle is located at 0.836 inch downstream the nozzle entrance plane. The local heating and cooling strips are applied at $2.86 \le x \le 3.73$ inches downstream of the nozzle entrance at station x=0 at 600°R and 400°R, respectively. At the exit of test section, x=9.24 inches, the values of the velocity curvatures at the wall for the heating, adiabatic, and cooling cases, i.e., the second derivative of boundary layer velocity profiles based on Eq. (A1), are -5.72×10^{-4}, -7.02×10^{-5}, and $+1.05\times10^{-3}$, respectively. Among these three cases, the value for the heating strip case is more negative than those of the cooling and adiabatic cases. This indicates the heating case is more stable than the other two cases. The N-Factor results from e^Malik code are plotted in Fig. 2 for the N-factor along the wall of the nozzle and test section where the heating and cooling strip is located at $2.86 \le x \le 3.73$ for a disturbance frequency of 14 kHz. The adiabatic case is also plotted in Fig. 2 for reference. The results of the local heating case at 600°R also show that the boundary layer has been stabilized. The results of the local cooling case at 400°R indicates the destabilization of the boundary layer on the nozzle and test-section wall. The N-factor theory which provides the N-factor from the initial instability point to the exit of the test section has shown the relative stability among three cases in Fig. 2. It should be noted that results obtained from both the curvature criteria and N-factor theory have presented the consistent conclusion--the heating strip stabilizes the boundary layer.

(2) Laminar Flow Supersonic Wind Tunnel (LFSWT) with Mach Number 1.6 Nozzle

This Laminar Flow Tunnel is 5.505 ft long including the nozzle and the test section. The throat of the nozzle is located at 0.557 ft downstream the nozzle inlet plane. Five locations of heating and cooling strips have been investigated. The specific locations selected along the nozzle or tunnel walls are shown in Fig. 3 with the initial instability on-set point of the boundary layer indicated. Three locations upstream of the instability on-set point are investigated for the effectiveness of the heating and cooling on the boundary layer stability. It can be seen from Figs. 4, 5 and 6 that the distance between the strip and the instability on-set point is very critical by examining the resulting N-factor distribution. The case of Position #2 seems more effective than those of Positions #1 and # 3. This can be interpreted that the heat energy is removed effectively from the boundary layer to the wall for the case using a heating strip at Position #2. Heating and cooling strips were applied to two locations downstream of the instability on-set point as shown in Fig. 3. It can be seen that the cooling strip at Position # 4 reduces the N-factor distribution impressively as shown in

Fig. 7. For Position #5, the cooling effects start further downstream than that of Position #4, as shown in Fig. 8. Thus it is recognized that the effect of removing heat energy to enhance the boundary layer stability should be properly located either using heating or cooling strips. The location of the strip relative to the on-set point of boundary layer instability is critical. In order to enhance the stability, in general, the heating strip should be applied upstream of the instability on-set point and the cooling strip downstream of the on-set point.

Furthermore, it is interesting to apply two strips on the wall: one heating strip upstream of the instability on-set point and the other, a cooling strip, downstream of the instability on-set point. Based on the above discussion, it is expected that the two strip arrangement will enhance stability and reduce the N-factor greatly. The results given in Fig. 9 are expected. However, Case II, shown in Fig. 9(b), produces the lowest N-factor values of the three cases in Fig. 9 by the combination of the upstream heating and downstream cooling.

Concluding Remarks

The present results show that heating and cooling in a local finite wall region can enhance and destabilize the stability of laminar boundary layers, respectively. Several previous classical theoretical and experimental studies have concluded that the boundary layer stability will be destabilized with uniform wall heating[8]. On the other hand, the uniformly cooled wall will enhance the boundary layer stability[9,10,11]. The present findings indicate that the stability is enhanced as the heating is applied upstream of the boundary layer instability initiated point. On the other hand, the cooling at the downstream of the instability on-set point also increases the stability of the boundary layer, and it is even more effective than those of upstream heating.

These may be rationalized as follows. The heat energy flowing downstream creates a positive temperature gradient in the vicinity of the wall ahead of the instability on-set location. This produces a cooling effect in the region near upstream and downstream the instability location and therefore enhances the boundary layer stability. The stability is reduced as cooling is utilized at the same location, since it produces heating effects at the instability point. The equivalent effects can be obtained by cooling the wall downstream of instability on-set point. These results have shown the same effects as the previous studies except that the present mechanism of cooling or heating is localized and limited to certain upstream regions of the wall, e.g., the leading edge (10%) of the flat plate or a region downstream of the nozzle throat. The latest theoretical study by Masad & Nayfeh[12] has provided similar results of heating effects which are limited to the subsonic flat plate case only. The experimental evidence obtained recently by Demetriades[13] has also indicated a similar trend by heating the throat region's wall to enhance the stability or delay the transition in the boundary layer of a supersonic nozzle. The application of strip heating and/or cooling to the quiet-tunnel's wall for boundary layer control seems feasible, especially since the heating and/or cooling regions are within a limited range of segments.

Acknowledgements

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Appendix

Effects on a Flat Plate

The wall temperature effects on the stability of the laminar boundary layer are investigated on a flat plate at supersonic speed to examine the viability of the proposed method. With specific temperature distributions by heating or cooling on the flat plate, the stability of the laminar boundary layer is examined to determine the effect on stability characteristics. Subsequently, the supersonic laminar flow can be controlled by cooling or heating the wall at specific locations on a flat plate.

Flat Plate in Supersonic Flow at M = 1.6

The plate with no pressure gradient is heated from the adiabatic temperature T_{aw} = 502°R to T_w = 802°R uniformly. The temperature distribution of the plate is calculated for three cases: T_{aw} = 502°R, T_w = 802°R local strip heated within $0 < x < 10\%$ of the plate, and T_w = 802°R uniformly heated. The temperature profiles at the end of the plate of these three cases are used to examine the velocity curvature of the boundary layer. The velocity curvature, based on the two-dimensional boundary layer momentum equation in the vicinity of a wall, with no suction or blowing, is given by Reshotko[3] as follows:

$$\mu_w u'' = -\frac{\partial\mu}{\partial T}\frac{\partial T}{\partial y}\frac{\partial u}{\partial y} + \frac{\partial p}{\partial x}, \quad at\ y=0 \tag{A1}$$

It is seen that the boundary layer velocity curvature depends on the temperature gradient. The velocity curvature of the uniformly heated case, T_w = 802°R, is positive since this case produces a large negative temperature gradient at the wall. The local heating strip case results in a positive temperature gradient at the wall downstream of the strip, and thus produces a negative velocity curvature. The velocity curvature at the end of the plate for the adiabatic and local strip heating cases are plotted in Fig. A1. For the local strip heating case, the second derivative of velocity at the wall has a negative value. Based on the criterion of Eq. (A1), the boundary layer stability of the locally heated case is enhanced. The N-factor of the spatial linear stability theory of e^N is computed by e^Malik code for several frequencies as shown in Fig. A2. The maximum N-factor for the adiabatic case is about 3.7 and may be reduced to about 1.8 for the local strip heating case. This indicates that the boundary layer stability is enhanced by heating upstream locally. But for the uniformly heated case, also shown in Fig. A2, the N-factor increases to 9 which destabilizes the boundary layer.

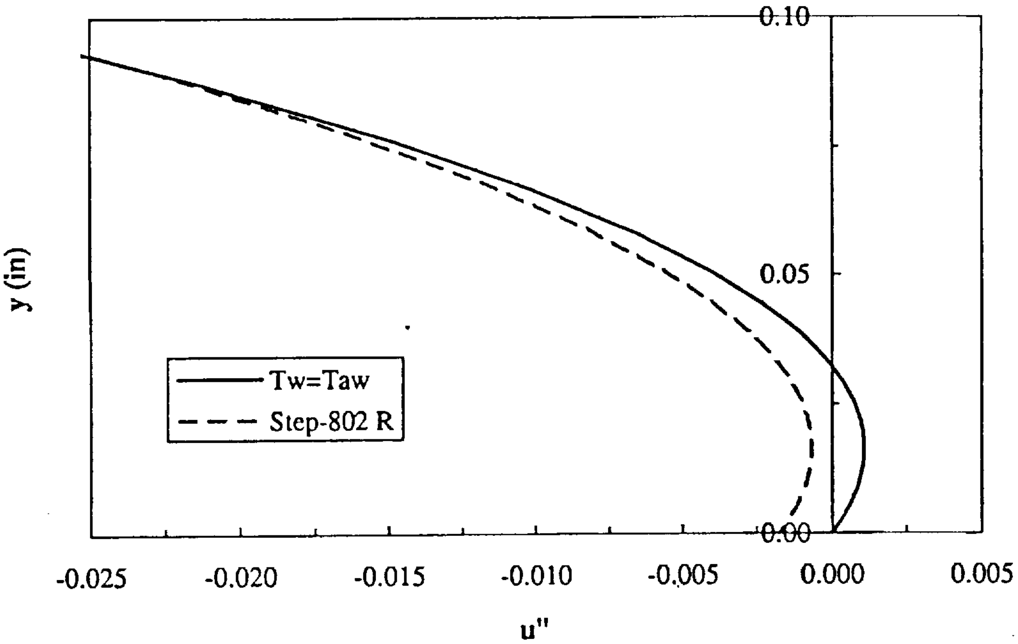

Figure A1. Velocity curvature at the end of a flat plate at supersonic speed for the adiabatic and local strip heating cases.

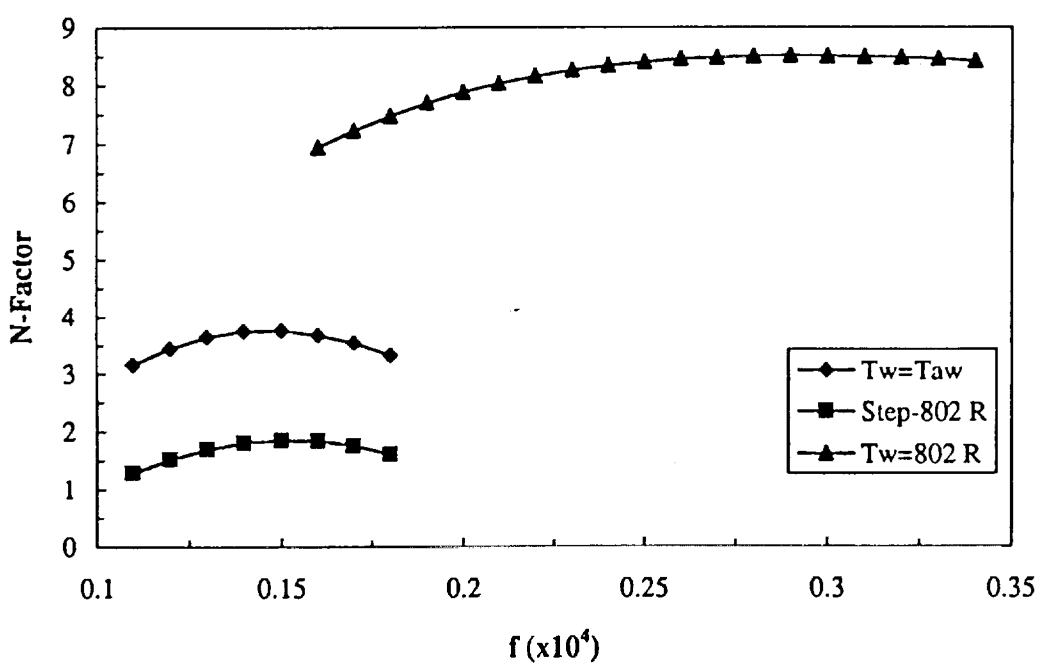

Figure A2. N-factor as a function of frequency for a flat plate at supersonic speed for an adiabatic wall, uniformly heated wall and local strip heating.

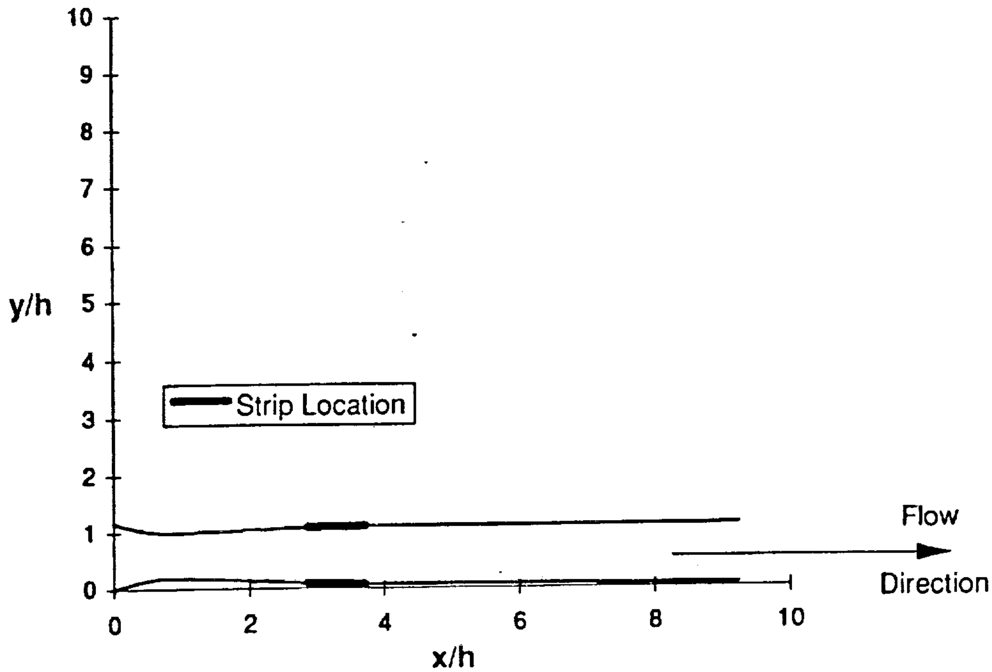

Figure 1. Heating/Cooling strip location on the Proof of Concept (PoC) Quiet Supersonic Wind Tunnel with Mach number 1.6 nozzle.

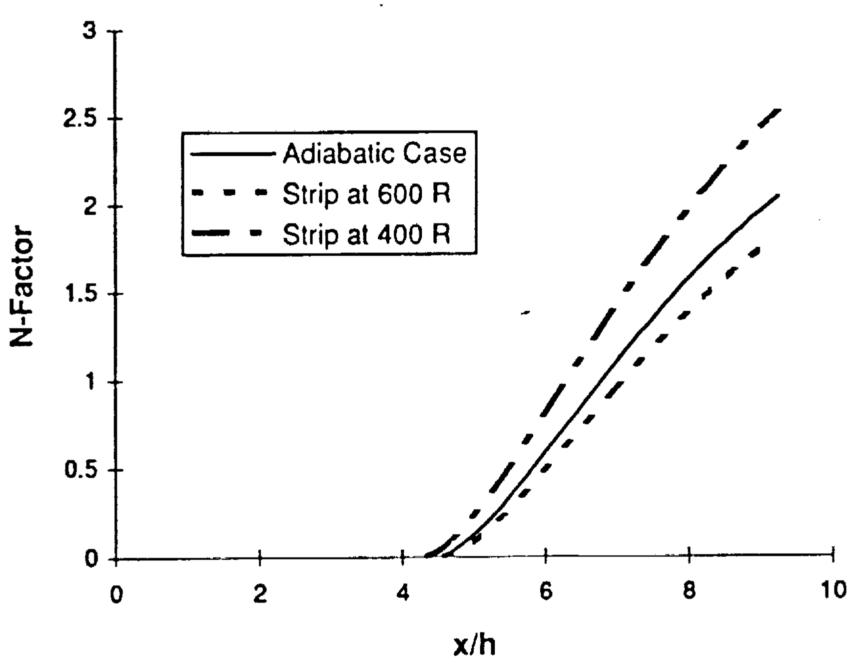

Figure 2. N-factor along the streamwise location for the adiabatic, local heating and local cooling cases on the PoC wind tunnel.

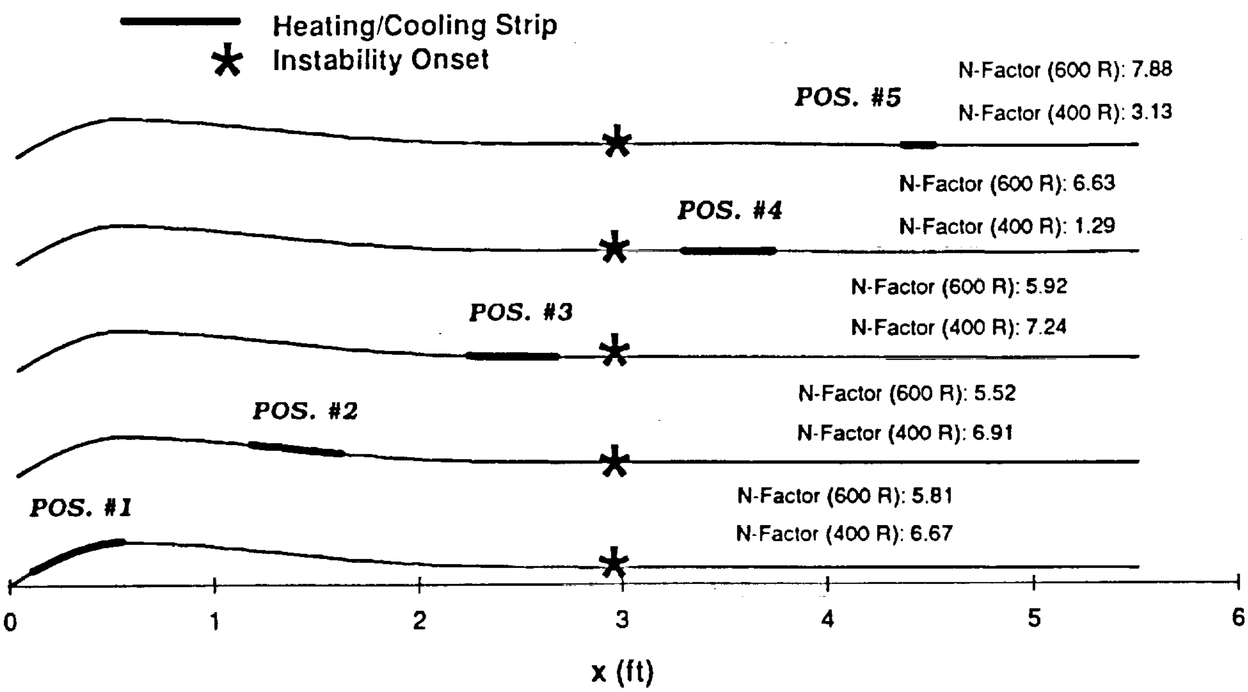

Figure 3. Heating/Cooling strip locations, instability onset locations and N-factor summary for the Laminar Flow Supersonic Wind Tunnel (LFSWT) cases.

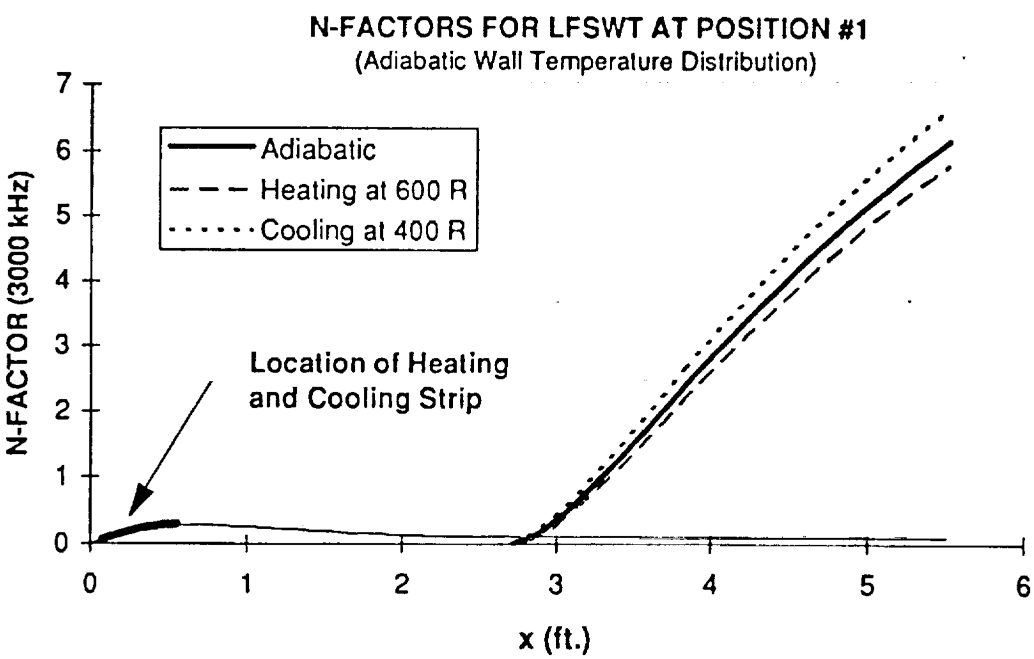

Figure 4. N-factor along the streamwise location for the adiabatic case, and local heating and local cooling cases at Location #1 on the LFSWT.

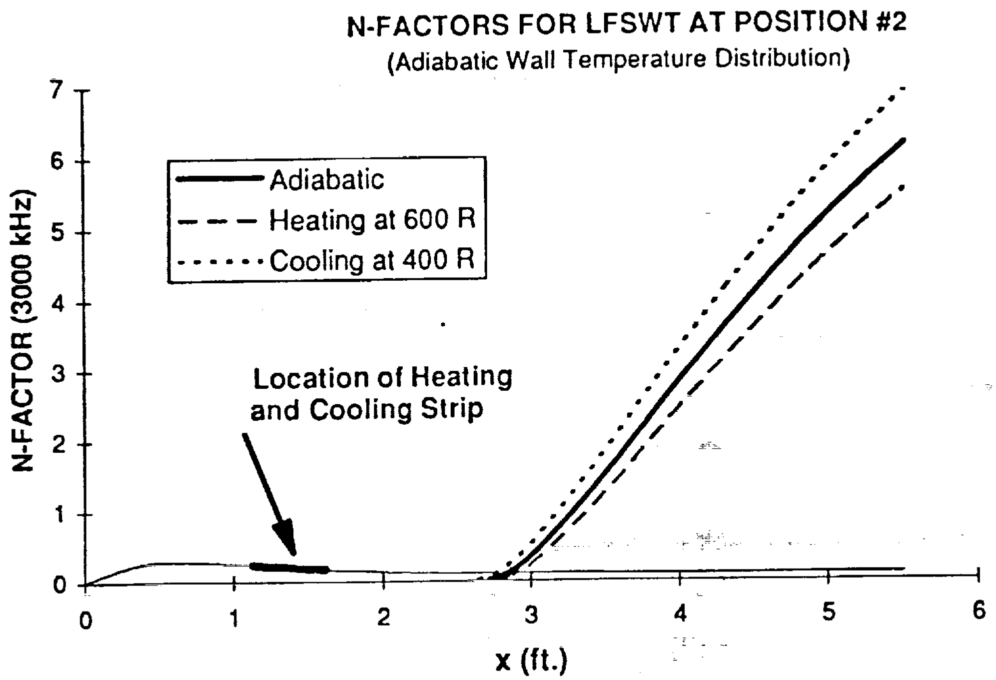

Figure 5. N-factor along the streamwise location for the adiabatic case, and local heating and local cooling cases at Location #2 on the LFSWT.

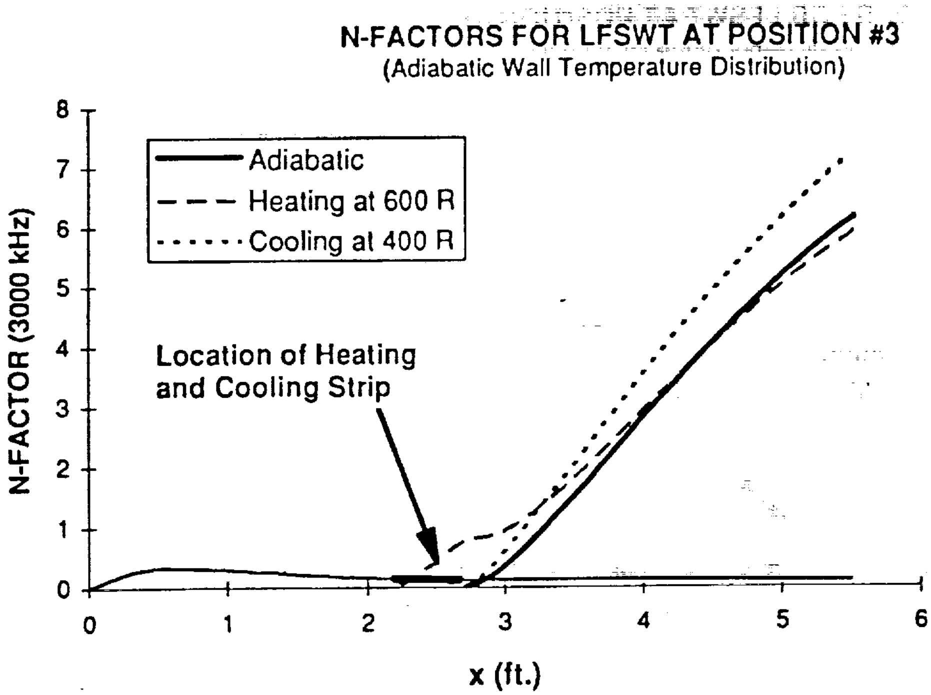

Figure 6. N-factor along the streamwise location for the adiabatic case, and local heating and local cooling cases at Location #3 on the LFSWT.

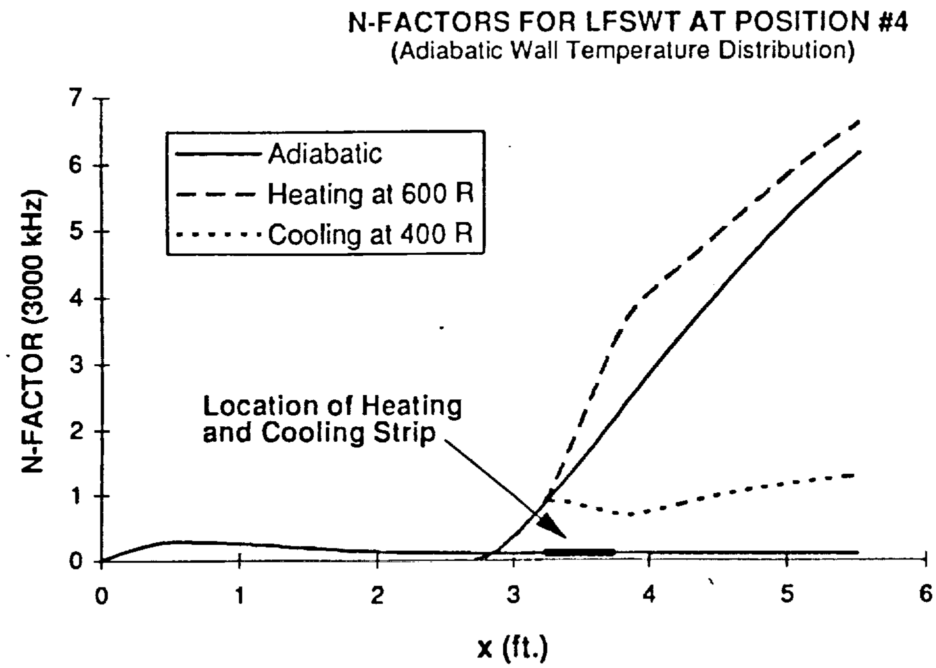

Figure 7. N-factor along the streamwise location for the adiabatic case, and local heating and local cooling cases at Location #4 on the LFSWT.

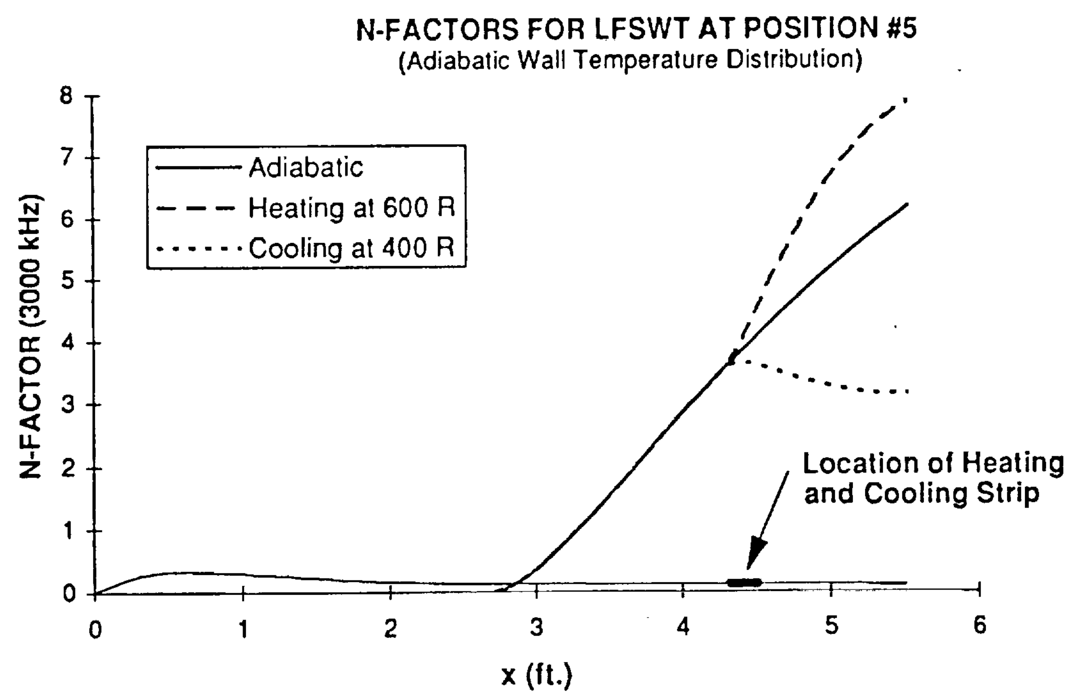

Figure 8. N-factor along the streamwise location for the adiabatic case, and local heating and local cooling cases at Location #5 on the LFSWT.

N-FACTORS ON LFSWT WITH HEATING & COOLING COMBINATION: CASE I

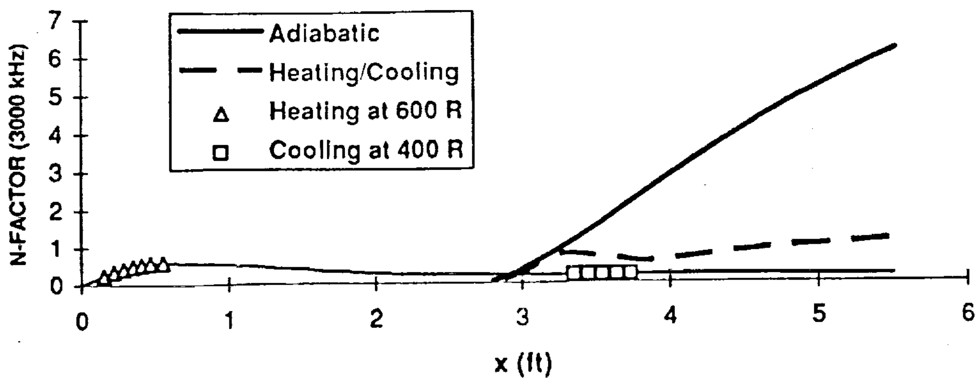

Figure 9(a). Case I

N-FACTORS ON LFSWT WITH HEATING & COOLING COMBINATION: CASE II

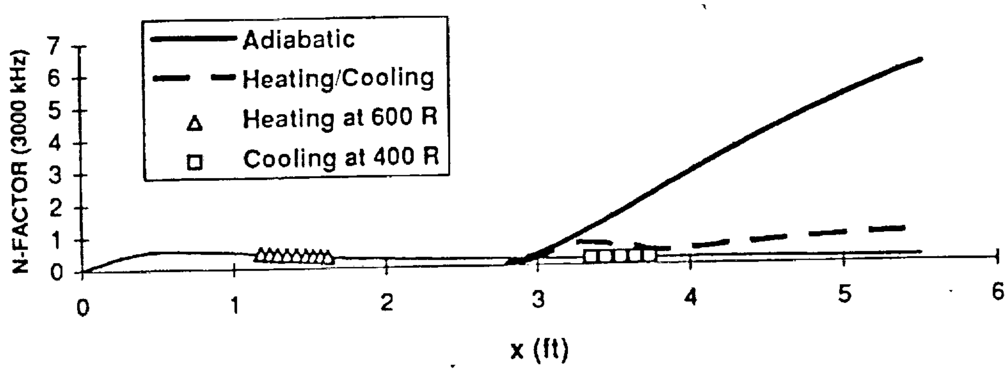

Figure 9(b). Case II

N-FACTORS ON LFSWT WITH HEATING & COOLING COMBINATION: CASE III

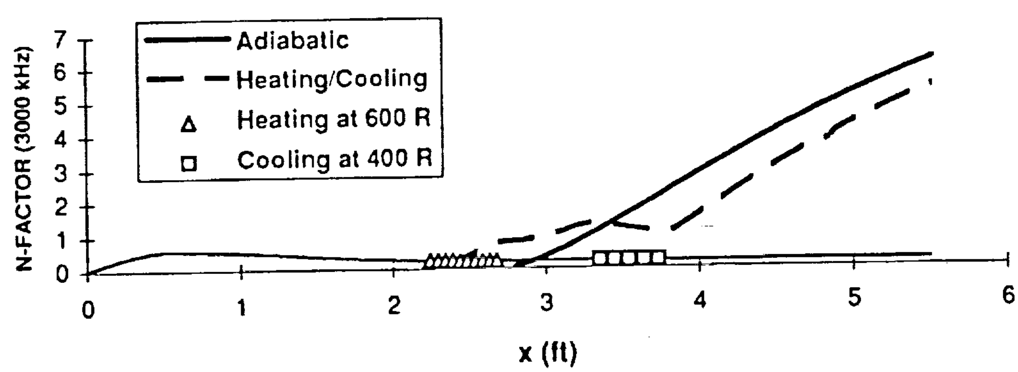

Figure 9(c). Case III

Figure 9. N-factor along streamwise location with local heating upstream and local cooling downstream of the instability onset on the LFSWT.

AIAA ENGINEERING NOTES

Wall Temperature Effects on the Stability of Laminar Boundary Layers

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Engineering Notes

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Nomenclature

h	= nozzle throat height
L	= distance from nozzle entrance
N	= N-factor in e^N for Tollmien-Schlichting Wave
M	= free-stream Mach Number
u	= boundary layer velocity in the x-direction
u''	= second velocity derivative in x
p	= pressure
x,y	= coordinates in streamwise and normal directions
T_{aw}	= adiabatic wall temperature, in °R
T_w	= wall temperature, in °R
μ_w	= viscosity coefficient

Introduction

A unique, low-disturbance supersonic wind tunnel is being developed at NASA to advance supersonic laminar flow studies at cruise Mach numbers for the High Speed Civil Transport. The distinctive aerodynamic features of this new quiet tunnel will be a low-disturbance settling camber, laminar boundary layers on the nozzle walls, and steady supersonic diffuser flow.

It is anticipated that design requirements of the nozzle for the full-scale Laminar Flow Supersonic Wind Tunnel must include the active control to laminar boundary layer on the nozzle wall to maintain the boundary layer laminar. In other words, the active control of supersonic

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transition on nozzle walls is necessary to preserve the laminar boundary layer. Because of the novel drive system, there is no easy way to implement a suction-type boundary layer device. The alternative is to use heating or cooling applied along the nozzle wall. Therefore, the effects of supersonic laminar flow with distributed wall surface heating and cooling for active control are studied and reported in this Engineering Note. To validate the prediction and analysis tools, a flat plate case is chosen in the study before the effects of wall temperature on a supersonic wind tunnel are evaluated.

Methods of Approach

The methods used to characterize the state of the stability are 1) Stability Modifier criterion based on the curvature of the boundary layer velocity and 2) a spatial linear stability method to computer N-factors for Tollmien-Schlichting waves. The latter method may be used to predict the transition on-set location as N-factor = 9 to 11. The calculation is carried out by two basic CFD codes: a compressible boundary layer code by Harris[1] and a linear stability code by Malik[2]. The detailed boundary layer velocity profiles calculated by the boundary layer code are utilized to qualitatively analyze the state of boundary layer stability based on the Stability Modifier criterion[3]. The outputs of the boundary layer code also provide the inputs into the Malik's Stability code to determine the value of the N-factor. The results of these two criteria have indicated the consistent prediction for the state of the boundary layer stability.

Effects on a Flat Plate and a Supersonic Nozzle:

The wall temperature effects on the stability of the laminar boundary layer are investigated on a flat plate at supersonic speed as well as a supersonic tunnel nozzle wall. With specific temperature distributions by heating or cooling on the flat plate or tunnel wall, the stability of the laminar boundary layers is examined to determine the effects of stability characteristics. Subsequently, the supersonic laminar flow can be controlled by cooling or heating the wall at specific locations on a flat plate or tunnel nozzle.

Flat Plate in Supersonic Flow at M = 1.6

The plate with no pressure gradient is heated from the adiabatic temperature $T_{aw} = 502°R$ to $T_w = 802°R$ uniformly. The temperature distribution of the plate are calculated for three cases: $T_{aw} = 502°R$, $T_w = 802°R$ local strip heated within $0 < x < 10\%$ of the plate, and $T_w = 802°R$ uniformly heated. The temperature profiles at the end of the plate of these three cases are used to examine the velocity curvature of the boundary layer. The velocity curvature, based on the two-dimensional boundary layer momentum equation in the vicinity of a wall, which is assumed no suction or blowing, is given by Reshotko[3] as follows:

$$\mu_w u'' = -\frac{\partial \mu}{\partial T}\frac{\partial T}{\partial y}\frac{\partial u}{\partial y} + \frac{\partial p}{\partial x}, \quad at \ y=0 \tag{1}$$

It is seen that the boundary layer velocity curvature depends on the temperature gradient. The velocity curvature of uniformly heated case, $T_w = 802°R$, is positive since this case produces a large negative temperature gradient at the wall. The local heating strip case results in a positive temperature gradient at the wall and thus produces a negative velocity curvature. The velocity curvature at the end of the plate for adiabatic and local strip heating cases are plotted in Fig. 1. For the local strip heating case, the second derivative of velocity at the wall has a negative value. Based on the criterion of Eq. (1), the boundary layer stability of the locally heated case is enhanced. The N-factor of the spatial linear stability theory of e^N is computed by e^Malik code for several frequencies as shown in Fig. 2. The maximum N factor for the adiabatic case is about 3.7 and may be reduced to about 1.8 for the local strip heating case. This indicates that the boundary layer stability is enhanced by heating upstream locally. But for the uniformly heated case also shown in Fig. 2, the N-factor increases to 9 which destabilizes the boundary layer.

Supersonic Nozzle at M = 1.6

Local heating and cooling strips are applied at $2.86 \leq X \leq 3.73$ (inch) downstream of the nozzle entrance at station X=0 at 600°R and 400°R, respectively. The total length of the NASA PoC nozzle and test section from the nozzle entrance to the test-section exit is 9.23 Inch (units) as shown in Fig. 3 with heating and cooling strips marked. At the exit of test section X=9.23 Inch, the values of the velocity curvatures at the wall for the heating, adiabatic, and cooling cases, i.e., the second derivative of boundary layer velocity profiles based on Eq.(1), are -5.72×10^{4}, - -7.02×10^{-5}, and $+1.05\times10^{-3}$, respectively. Among these three cases, the value of the heating strip case is negative and smaller than those of the cooling and adiabatic cases. This indicates the heating case is more stable than the other two cases. The results of N-Factor from e^Malik code are plotted in Fig. 3 for the N-factor along the wall of the nozzle and test section where the heating and cooling strip is located at $2.86 \leq X \leq 3.73$ for a disturbance frequency of 14 KHz. The adiabatic case is also plotted in Fig. 3 for reference. The results of the local heating case with 600°R also show that the boundary layer has been stabilized . The results of the local cooling case with 400°R indicates the destabilization of the boundary layer on the nozzle and test-section wall. The N-factor theory which provides the N-factor from the initial instability point to the exit of the test section has shown the relative stability among three cases in Fig. 3. It should be noted that results obtained from both the curvature criteria and N-factor theory have presented the consistent conclusion--the heating strip stabilizes the boundary layer.

Concluding Remarks

The present results show that heating and cooling in a local finite wall region can enhance and destabilize the stability of laminar boundary layers, respectively. Several previous classical theoretical and experimental studies have concluded that the boundary layer stability will be destabilized with uniform wall heating[4]. On the other hand, the uniformly cooled wall will enhance the boundary layer[5,6,7]. The present findings indicate that the stability is enhanced as the heating is applied at the upstream of the boundary layer instability initiated point. Thus, the heating energy flowing downstream creates a positive temperature gradient in the vicinity of the wall ahead of the instability occurring location. This produces a cooling effects in the region near upstream the instability location and therefore enhances the boundary layer stability. The stability is reduced as the cooling is utilized at the same location, since it produces heating effects at the instability point. These results seem to show the same effects as the previous studies except the present mechanism of cooling or heating is localized and limited in certain upstream region of a flat plate, e.g., the leading edge (10%) of the flat plate or a region downstream of the nozzle throat. The latest theoretical study by Masad & Nayfeh[8] has provided similar results limited to the subsonic flat plate case only. The experimental evidence obtained by Demetriades[8] recently has also indicated a similar trend by heating the throat region's wall to enhance the stability or delay the transition in the boundary layer of a supersonic nozzle. The application of strip heating to the quiet-tunnel's boundary layer control seems feasible, especially since the heating region is within a limited range of segments.

Acknowledgements

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Captions

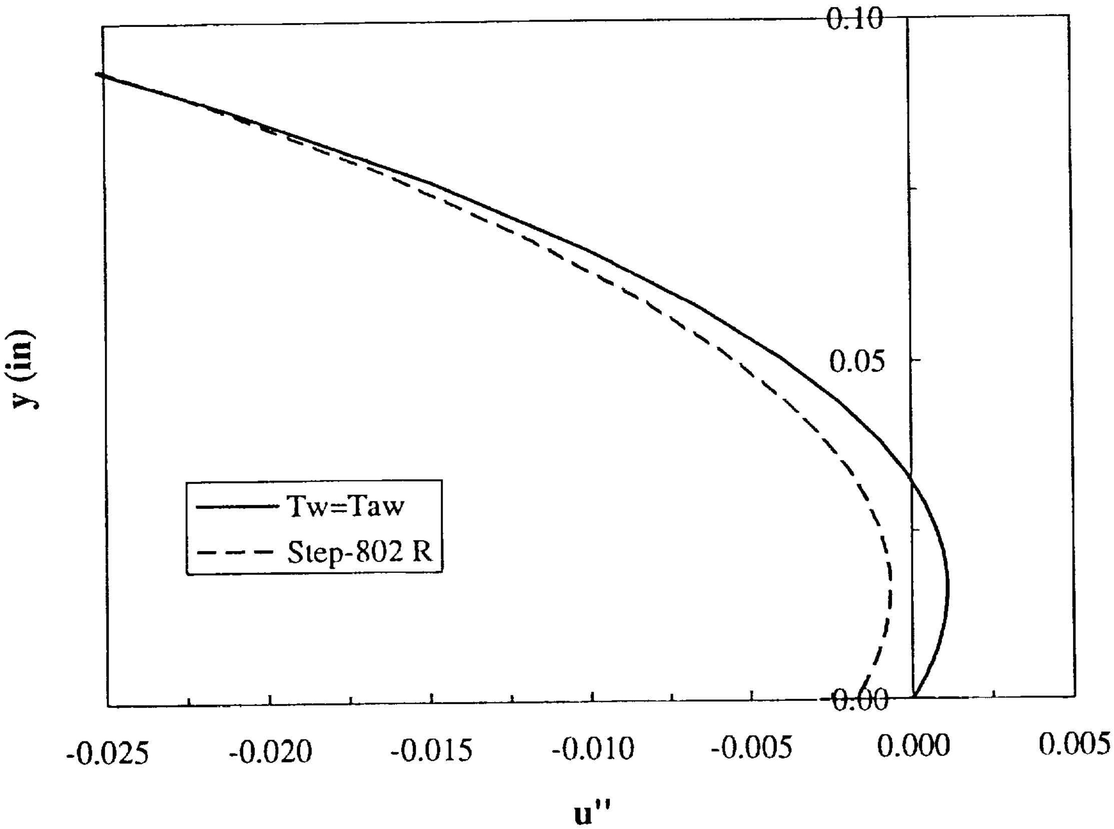
Figure 1. Second Velocity Derivative Profile for a Flat Plate Laminar Boundary Layer with Strip Heating

Figure 2. N Factors with Strip Heating for a Flat Plate

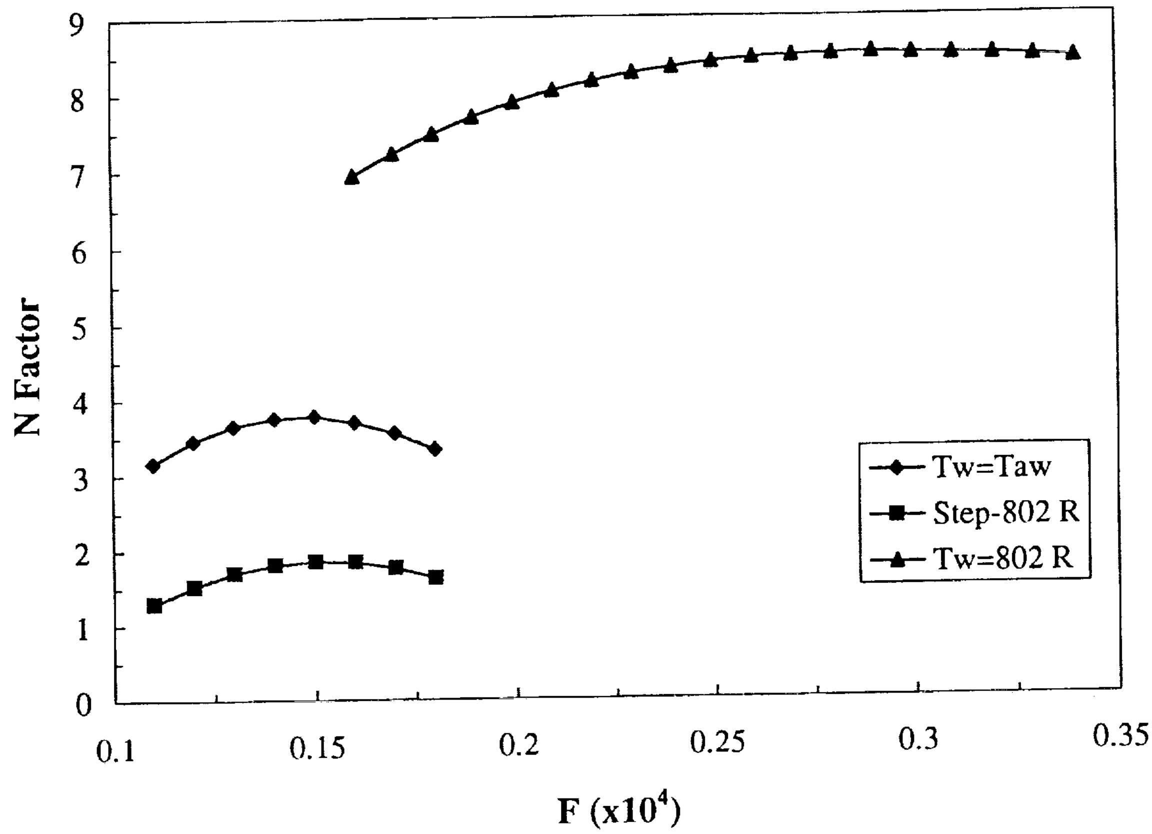
Figure 3. N Factor Growth with the Heating/Cooling Strip Located at $2.86 \leq X \leq 3.73$ for a Disturbance Frequency of 14 kHz for a NASA supersonic tunnel

Figure 3a. Heating/Cooling Strip Location on the Nozzle and Test Section

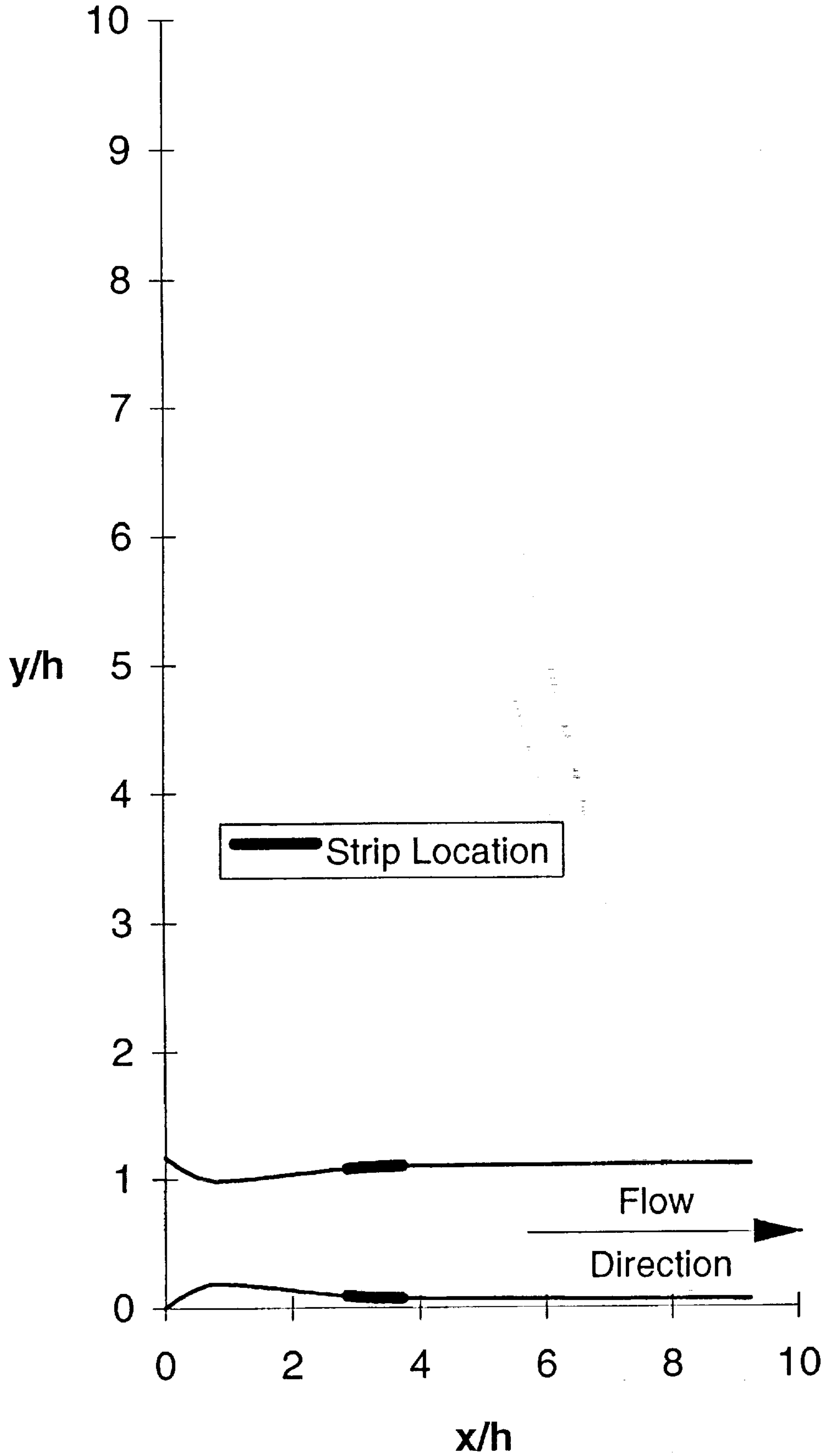
Figure 3b. N Factor Growth along the Nozzle and Test Section



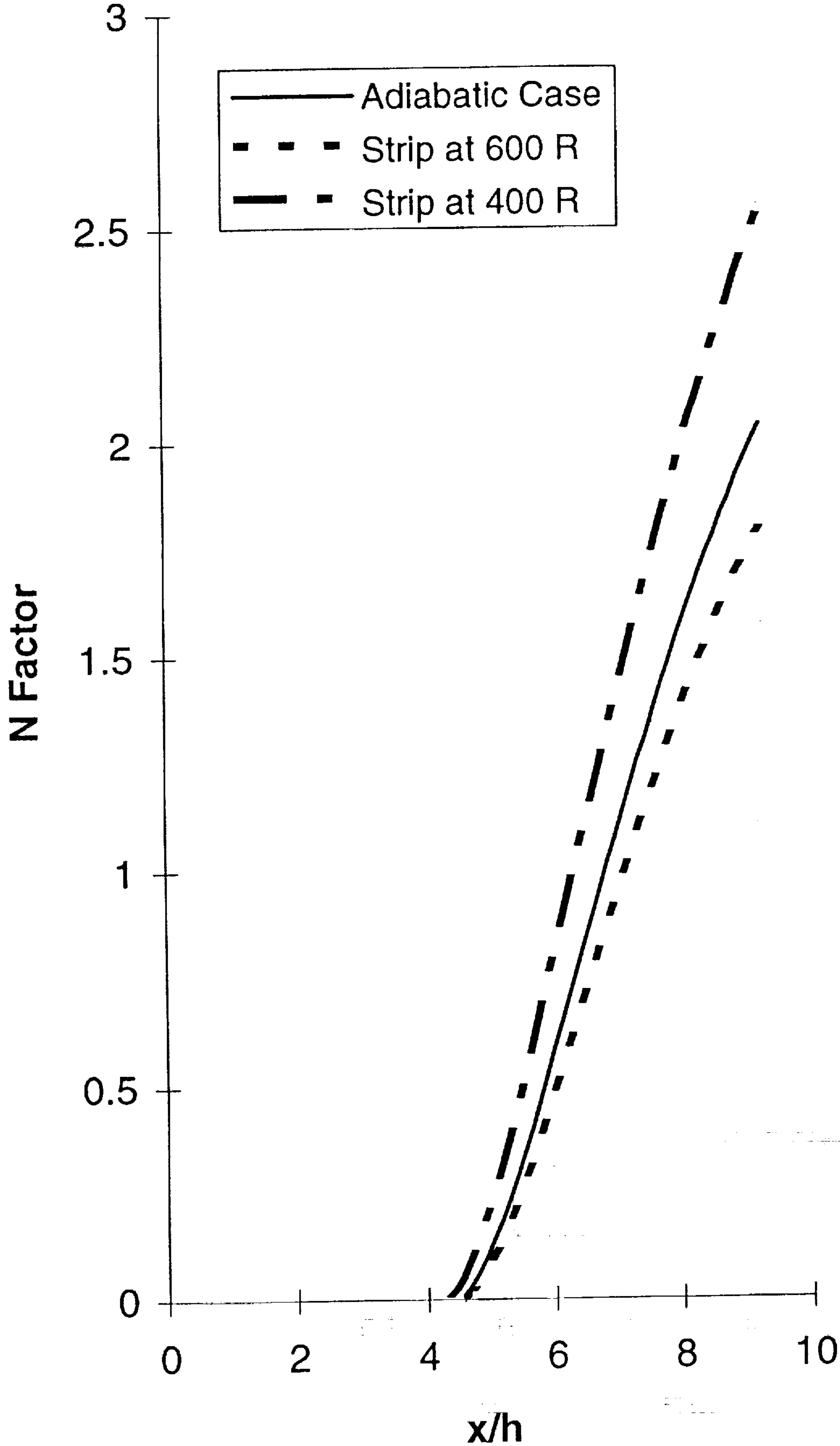
y (in)
0.10
0.05
0.00
-0.025
-0.020
-0.015
-0.010
-0.005
0.000
0.005
u''
Tw=Taw
Step-802 R



N Factor
F (x10^4)
Tw=Taw
Step-802 R
Tw=802 R



y/h
10
9
8
7
6
5
4
3
2
1
0
Strip Location
Flow
Direction
0
2
4
6
8
10
x/h


Adiabatic Case
Strip at 600 R
Strip at 400 R
N Factor
x/h
3
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10